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Comparison of Magnetic Field and Iron Loss Models for 2-Dimensional Magnetic Anisotropic Properties

***Abstract**. In numerical analysis of electromagnetic equipment that contains magnetically anisotropic material, the model considering magnetic anisotropy should be used. In this work, conventionally proposed magnetic field and iron loss models that can take anisotropic magnetic property into account, are applied to some models to evaluate its accuracy. The two-axis magnetic field model can obtain similar distribution to the magnetic field by θHB model. Therefore by using BAI iron-loss model with two-axis magnetic field model, relatively accurate iron loss value can be estimated.*

***Streszczenie.** Przy projektowaniu urządzeń magnetycznych z anizotropowym materiałem te właściwości anizotropowe powinny być brane pod uwagę. W przedstawionej pracy użyto konwencjonalnego HB modelu do obliczeń. Wyniki porównano z modelem kątowym θHB. Sprawdzono także model BAI. (**Porównanie różnych modeli strat przy obliczaniu dwuwymiarowym właściwości anizotropowych**)*

Keywords: Anisotropy, magnetic field analysis, 2D magnetic property
Słowa kluczowe: anizotropia, analiza pola magnetycznego.

Introduction

The silicon steel sheets are used for the cores of electrical equipment such as generators, transformers, and motors [1]. Since the steel sheets have complicated magnetic properties, such as anisotropy, and non-linearity, numerical simulation techniques are applied to design electrical equipments to obtain better performance by taking full advantage of silicon steel sheets [2]. So far, many analysis methods are proposed to calculate the magnetic field and iron loss in electrical equipments made of the silicon steel sheets [3][4][5]. Especially in case of grain-oriented silicon steel (GO), the model considering magnetic anisotropy should be used to analyze magnetic field and iron loss. However, a precise anisotropy model requires much more computing time and sometimes does not numerically converge because of the data error caused by measurement difficulty of 2D magnetic property. In this paper, we compare the magnetic fields and iron losses calculated by some analysis models, to evaluate the accuracy of each model, expecting a simple model might be useful to obtain good approximation.

Analysis Model and Method

The magnetic field distributions calculated by the four analysis methods, which are (i) isotropic method, (ii) two-axis anisotropic method, (iii) φ anisotropic method [6] and (iv) θHB anisotropic method [7], are investigated by using finite element method [8]. In the isotropic method, the magnetic property between magnetic flux density B and magnetic field H is supposed to be isotropic and calculated with only one H-B property. In the two-axis anisotropic method, the B is separated to components of easy magnetization axis and hard axis. Then different B-H property is used for each component. In the φ anisotropic method, H-B properties are different in respective B directions and it is assumed that the B is parallel to the H. In the θHB anisotropic method, the angle, θHB, between B and H is considered. In the anisotropic material such as silicon steel sheet, the direction of magnetic field, θH, is generally different from that of magnetic flux density, θB. Fig. 1 shows the relation of the B and the H in the θHB anisotropic method. The two-dimensional magnetic property data shown in Fig.2 is necessary to use θHB method.

The iron loss model used in this work is a measured iron loss W property data obtained by conventional testing method or 2 dimensional magnetic measurements [9][10]. The iron loss of each finite element is calculated from magnetic field by using iron loss model and total core loss is obtained by summing all elements iron loss. In this work, the four iron loss models described below are applied.

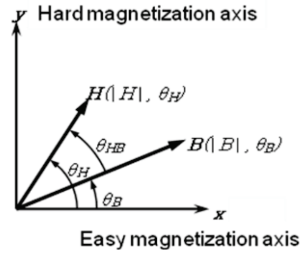


Fig.1. Relation of magnetic flux density, B, and magnetic field, H

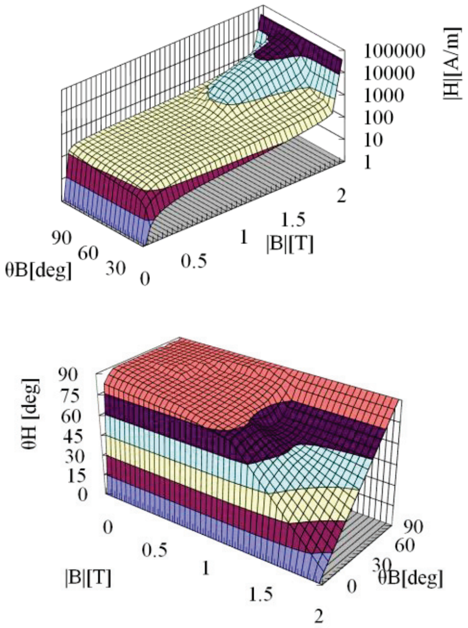


Fig.2. Measured example of 2D magnetic property of GO steel

(A) In the isotropic iron loss model, the loss is a function of only the absolute value of B. It is supposed that B-W property curve is same to all direction in the plane of silicon steel sheets. (B) In the two axis iron loss model, the iron loss of each component is calculated from corresponding B-W property and total iron loss is obtained by summing them. (C) In the φ anisotropic method, H-B and B-W properties are different in respective B directions and it is assumed that the B is parallel to the H. The amplitude of maximum B and the angle form easy axis are calculated from magnetic field, then corresponding B-W curve is used to calculate iron loss. (D) The BAI iron loss model which calculates the iron loss as a function of Bmax (B maximum values), α (Axis ratio of B vector trace: = minimum B/ maximum B), and θB (Inclination angle: = direction of maximum B against the magnetic easy axis). Fig.3 shows the schematic illustration of BAI model and measured example of 2D B-W property.

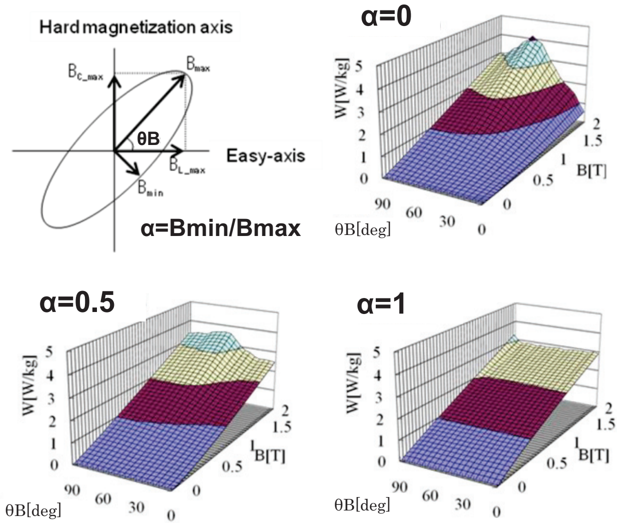


Fig.3. BAI iron loss model and measured example of 2D iron loss property of GO steel

Table 1. The combination of magnetic field and iron loss models

Iron Loss Model / Magnetic Field analysis Model	(A) Isotropic	(B) Two-axis anisotropic	(C) φ anisotropic	(D) BAI
(1) Isotropic model	1A	1B	1C	1D
(2) Two-Axis anisotropic	-	2B	2C	2D
(3) φ-anisotropic	-	-	3C	3D
(4) θHB-anisotropic	-	-	-	4D

In this work, the combination of magnetic field analysis model and iron loss models shown in table 1 are evaluated. Usually, a combination colored by yellow is applied. The combination of θHB and BAI model is thought to be best solution and gives the most accurate answer in these combinations. So the result by another combination are compared with θHB and BAI model's result. However, the results by φ-anisotropic magnetic field model was not evaluated because FEM magnetic field calculation was not converged in case of GO steel. The improvement of convergence of φ-anisotropic model for GO steel magnetic property is our future work.

The magnetic field of the model shown in Fig.4 is analyzed by FEM using each magnetic anisotropy model, and then iron loss is calculated. The convergence criterion of FEM nonlinear calculation is the maximum difference between the current nonlinear iteration's magnetic flux density and the previous iteration's one. The convergence criterion is set to 10^{-4}. A basic structure of this model is a solenoid coil of two dimensions and magnetic flux is almost alternative flux. The coil is filled with GO steel which has easy magnetization axis parallel to x-axis. There is an inner sample of 30mmx30mm at the center. The inner sample's easy axis is inclined 30-degree to x-axis. Magnetic field and iron loss at center 80mm x 80mm area is compared. There are no air-gaps between inner and outer sample. The coil current is given as sine wave of 50 Hertz. Fig.5 shows another model to evaluate rotating magnetic field. The square-shaped GO steel sample is magnetized by orthogonally arranged two coils. To the each coil, sine wave current is imposed and each current has phase difference of 90 degree. We changed the easy magnetization axis of inner sample. The first model's easy axis is x-axis. In the second model, the easy axis inclines 30-degree to x-axis. Outer sample's easy axis is x-axis in common. Also in these models, there are no air-gaps between inner and outer samples.

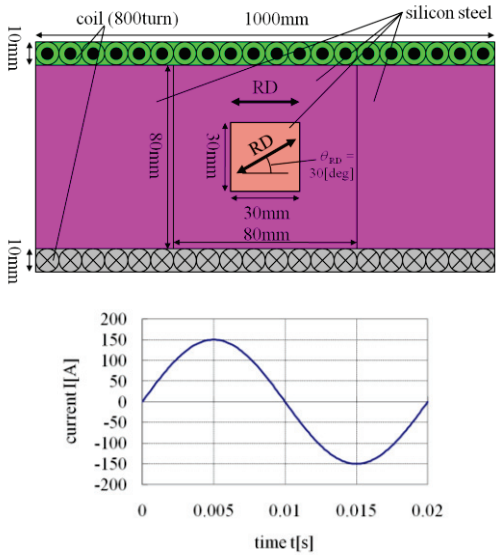


Fig. 4. Analysis model for alternative magnetic flux

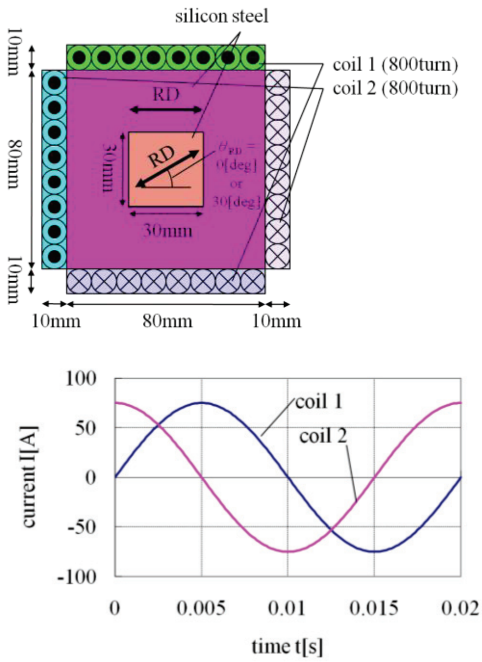


Fig.5. Analysis model for rotating magnetic flux

Result and discussion

Fig.6 shows the calculated magnetic field of the model shown in Fig.4. The distributions of B maximum values, α and θB at 80 mm x 80 mm region surrounding centre 30 mm x 30 mm area are shown in colour map. The results by the φ anisotropic method are eliminated because we could not obtain converged magnetic fields in FEM calculation. The result by isotropic model is quite expected. Since magnetic field in a solenoid coil is homogeneous, Bmax is a flat distribution and α and θB are zero. Therefore the distribution is quite different from the field by θHB method and it can be expected that the calculated iron loss is also quite different from the result by θHB and BAI model. On the other hand, the magnetic flux density by two-axis anisotropic model is basically similar to the result by θHB method. There are relatively large B values at the inner sample in case of the two-axis anisotropic method.

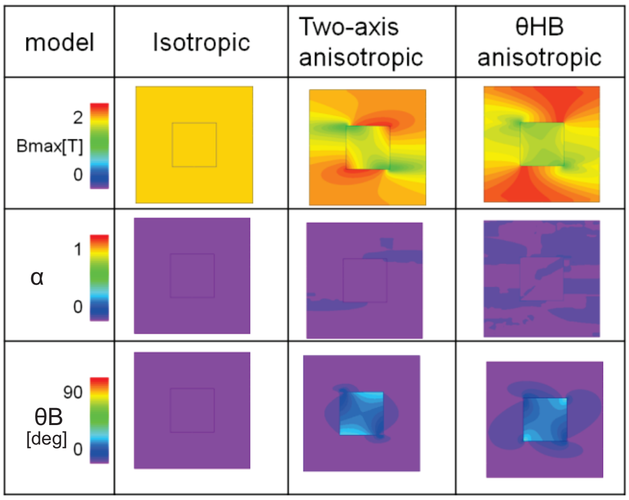
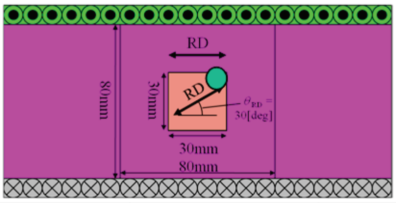


Fig.6. Calculated magnetic filed of alternative magnetic flux model.



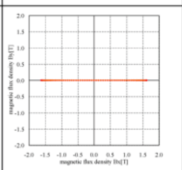
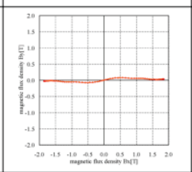
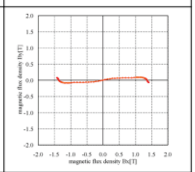
	Isotropic	Two-axis anisotropic	*θ* HB anisotropic
Vector trace			
Bmax α θB	1.63 [T] 0.0 [-] 0.0 [deg]	1.85 [T] 0.0 [-] 29.1 [deg]	1.41 [T] 0.0 [-] 32.7 [deg]

Fig.7. B vector trace of calculated magnetic field at the right top corner of inner sample.

Fig.7 shows a B vector trace at the right top point of inner sample. Despite the easy axis of inner sample is inclined 30 degree to the x-axis, the loci shows that the direction of B vector is almost x-axis. The reason of this is the magnetic flux direction of outer sample is x-axis and the tangential component of B vector in the inner sample reflects that distribution. This θB is defined as the angle from the easy axis. Therefore 29.1 degree means the direction of magnetic flux is almost x-axis. This α value is almost same as θHB model. Bmax by two-axis model is higher than that by θHB method. It is considered that the shield effect of the outer GO steel is more weakly evaluated by the two-axis method. The calculated iron loss by each model is shown in Fig.8. The result by isotropic magnetic field model is omitted because it is very different from the field by θHB method. The combination of two-axis magnetic field and two-axis iron loss model underestimates iron loss since it does not consider the effect of Inclination angle θB and α. By considering the effect of Inclination angle with φ-anisotropic iron loss model, the iron loss increases but its contribution is relatively small in this case. By taking account the effect of α into the loss calculation with BAI model, appropriate iron loss value and distribution is obtained.

Magnetic field	(2)Two-axis anisotropic model			(4)θHB model
Iron loss	(B)Two-axis	(C)φ	(D)BAI	(D)BAI
Calculated iron loss Iron loss [W/kg] 3 0				
Average iron loss [W/kg]	0.387	0.413	0.482	0.490

Fig.8. Calculated iron loss of alternative magnetic flux model.

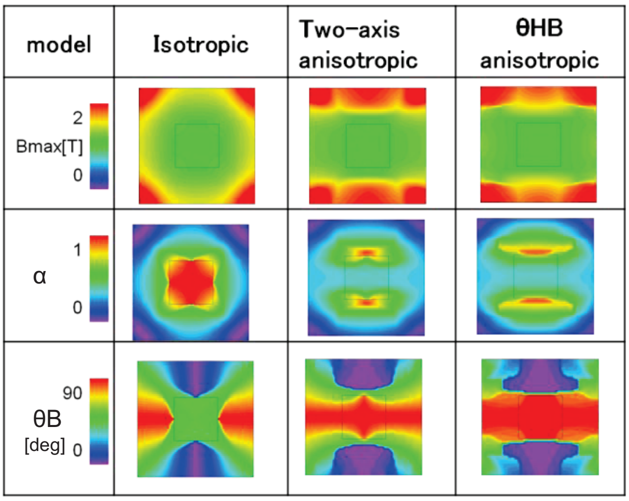
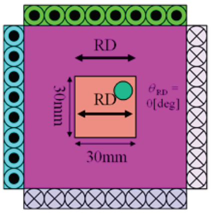


Fig.9. Calculated magnetic filed of rotating magnetic flux model.

Fig.9 shows the calculated magnetic fields of the rotating magnetic flux model shown in Fig.5 by three models. The magnetic field by isotropic model, strong magnetic field exists at the corner of the sample and magnetic flux density at the center is nearly rotating magnetic flux. The distribution is quite different from the field by θHB method. On the other hand, the field by two-axis anisotropic model is a good approximation of the θHB method. Because of the high permeability of x direction, strong magnetic flux density exists along the upper and lower coil. And the magnetic flux density of easy axis component decays at short distance. That is the reason why, inclination angle at center is almost 90 degree. nisotropic magnetic field model in case of GO property.Fig.10 is a B vector trace at the right top point of inner sample. Orange line shows the actual vector trace and black line means the approximated ellipse shape to apply the BAI iron loss model. Compared with θHB method, the Bmax by two-axis model is very close but α is over-estimated and Inclination angle θB is small value. However, as shown in the Fig.3, the change of iron loss against α and θB is relatively small at the range that the α is more than 0.5. Therefore it is expected that the difference of α and θB at this range does not strongly affect to estimate iron loss. The calculated iron loss distributions by each model are shown in Fig.11. The combination of two-axis magnetic field and iron loss model underestimates iron loss since it does not consider the effect of inclination angle θB and α. Considering the effect of Inclination angle with the φ-iron loss model, the loss value increases and its contribution is almost same as the effect of α. By using the BAI model, similar iron loss distribution is obtained. The iron loss value is about 8% larger than that by θHB model. This over estimation is mainly caused by inclined magnetic field near the corner of sample.



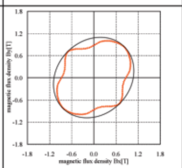
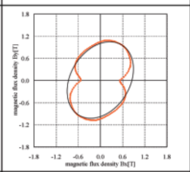
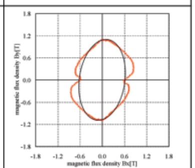
	Isotropic	Two-axis anisotropic	θ HB anisotropic
Vector trace			
Bmax α θB	1. 17[T] 0.85 [-] 45.0 [deg]	1.12 [T] 0.71 [-] 58.3 [deg]	1.09 [T] 0.57 [-] 82.3 [deg]

Fig.10. B vector trace of calculated magnetic field at the right top corner of inner sample. (Orange: actual vector trace, black: approximated ellipse)

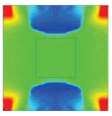
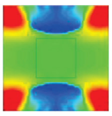
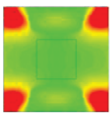
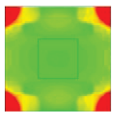
Magnetic field	(2)Two-axis anisotropic model			(4)θHB model
Iron loss	(B)Two-axis	(C)φ	(D)BAI	(D)BAI
Calculated iron loss Iron loss [W/kg] 3 … 0				
Average iron loss [W/kg]	1.54	1.89	2.23	2.10

Fig.11. Calculated iron loss of rotating magnetic flux model.

Fig.12 shows the calculated magnetic fields of the rotating magnetic flux model which has the inner sample of 30 degree-inclined easy magnetization axis against the outer sample's easy-axis.The result by isotropic model is same as former model. The field by two-axis anisotropic model is tending to penetrate to the inner sample. This causes a difference of magnetic field distribution especially at inner sample. Fig.13 is the B vector trace at the right top point of inner sample. Compared with θHB method, the field by two axis method is long oval with larger B maximum. Also for this model, the effect of the Inclination angle θB and α is large to calculate iron loss as shown in Fig.14. By using the BAI model, a similar iron loss value is obtained with two-axis anisotropic magnetic field model.

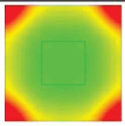
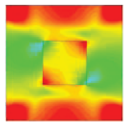
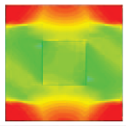
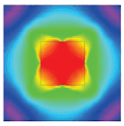
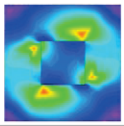
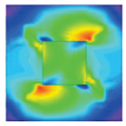
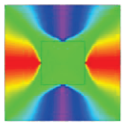
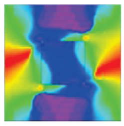
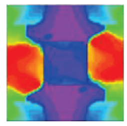
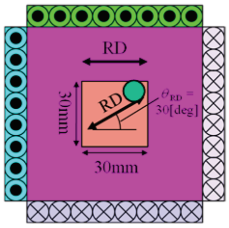
model	Isotropic	Two-axis anisotropic	θHB anisotropic
Bmax[T] 2 … 0			
α 1 … 0			
θB [deg] 90 … 0			

Fig.12. Calculated magnetic filed of rotating magnetic flux model.



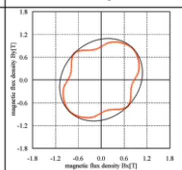
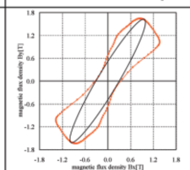
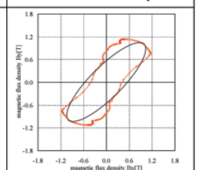
	Isotropic	Two-axis anisotropic	θ HB anisotropic
Vector trace			
Bmax α θB	1. 17[T] 0.85 [-] 45.0 [deg]	1.87 [T] 0.15 [-] 29.7 [deg]	1.41 [T] 0.29 [-] 15.5 [deg]

Fig.13. B vector trace of calculated magnetic field at the right top corner of inner sample. (Orange: actual vector trace, black: approximated ellipse)

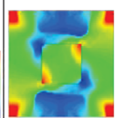
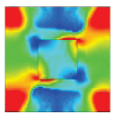
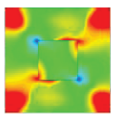
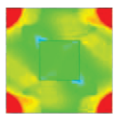
Magnetic field	(2)Two-axis anisotropic model			(4)θHB model
Iron loss	(B)Two-axis	(C)φ	(D)BAI	(D)BAI
Calculated iron loss Iron loss [W/kg] 3 … 0				
Average iron loss [W/kg]	1.53	1.80	2.18	2.09

Fig.14 Calculated iron loss of rotating magnetic flux model.

Conclusions

1. In case of the model that includes GO steel, the magnetic field calculated by two-axis model is relatively similar to the result by θHB anisotropic model.
2. The two-axis and φ-anisotropic iron loss models underestimate the iron loss than BAI model. The influence of rotating magnetic field to the iron loss is large in case of any model. This indicates relatively accurate iron loss value can be estimated by using BAI iron-loss model with two-axis magnetic field model.

3. The change of iron loss against α and θB is relatively small at the range that the α is more than 0.5. The difference of α and θB at this range does not strongly affect to estimate iron loss.
4. Since the two-axis magnetic field model has a better convergence than θHB anisotropic model, the combination of two-axis magnetic field model and BAI iron-loss model can be a practical simulation scheme to evaluate the magnetic field and iron loss in electric equipment with the grain-oriented silicon steel.

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